Conference Note: A Taxonomy of Extended Radio Sources in Clusters of Galaxies

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At the request of the conference attendees, we have compiled a classification of extended radio sources in clusters. These range from scales of tens of parsecs to over a megaparsec in scale, and include both sources associated with AGN and sources thought to derive from the electron population in the ionized ICM. We pay special attention to distinguishing between the types of AGN in the cores of cooling flow clusters and between the multiple classes of objects referred to over the years as "radio relics." We suggest new names based on physical arguments for some of these classes of objects where their commonly used names are inappropriate or confusing.

1. Introduction

This conference note was inspired by the frequent lamentation during discussions of radio halos and relics that the nomenclature for these sources is confusing. "We need a new name for relics" has become a common refrain, since three physically distinct sources are all referred to in the literature as "radio relics," and at least one of them is not a relic of anything. The phenomenological approach used to classify these diffuse sources has produced this confusion, whereas a classification scheme based on physical properties of the sources would suffer no such drawback. To make matters worse, the radio galaxies at the centers of clusters are often referred to by a Fanaroff-Reilly type when in fact neither an FR I nor FR II classification is appropriate. This short paper, then, is intended to clear up this confusion to the extent possible. The confusion will only go away, however, if the classifications described herein are adopted by the community at large and, of course, if nature kindly agrees to follow our theoretical pictures of these phenomena. We propose several new names for sources previously classified as "radio relics" and suggest, with no small hint of hubris, that all who read this article start using them.

We have attempted to classify the sources discussed herein by their current physical interpretations rather than by their phenomenological properties, as this promises to establish a firmer basis for our classifications. While some of these physical interpretations may need to be modified or re-worked entirely as the quality of the data improves, we view this as a natural component of any scientific endeavor. It is even possible that some of the sources we identify here will ultimately require new, as yet unimagined physical interpretations. If some of the sources we mention need to be re-classified in future, so be it. This article lays the groundwork for a rationalized classification scheme for cluster radio sources, and we expect (and hope!) that this scheme will be built upon in the future.

2. Classifications

The numerous types of large-scale radio sources in clusters of galaxies span approximately 5 orders of magnitude in linear size and possess a wide range of radio properties. They can be broken down into two basic classes: those associated with AGN, and those associated with the ICM. The first of these two classes is the larger of the two, comprising all but three of the source types we will discuss here. This first class can be broken down further into sources associated with currently active AGN and those associated with extinct or dying AGN. Of the three types not associated with AGN, two appear to be associated with cluster mergers while one, the "mini-halo," has an even less certain origin and may not even be a distinct class of source. Here, then, are the 9 classes of extended cluster radio sources with their fundamental observational properties and generally agreed upon (though occasionally uncertain) physical origins. We have arranged them roughly in order of increasing linear size. The basic properties of these sources are summarized in Table 1.

2.1. *Sources Associated With Active AGN*

VLBI Core: The smallest of the sources discussed here, these small-scale jets are unresolved in single-dish and small array observations. At the milli-arcsecond resolution of VLBI they are resolved into multiple knots of emission, sometimes with accompanying diffuse emission, in one- or two-sided jets plus a core associated with the central black hole. Typical size scales of these jets are ten to a hundred parsecs. Proper motions of the knots are observed over timescales of several months,

TABLE 1. SUMMARY OF PROPERTIES OF CLUSTER RADIO SOURCES

Type	Radio Source Characteristics				Relationship to Hot Gas	Prototype
	Size	Morphology	α	Polarization		
Associated with active radio galaxies:						
VLBI Core	10–100 pc	multiple point sources	-0.5	few %	None	3C 345
Confined Cluster Core Source	10 kpc	core + halo that may or may not include distinct lobes	$\lesssim -1.5$	$\lesssim 60\%^{\dagger\star}$	Anti-correlated	Perseus
Radio Galaxy	few$\times 10^2$ kpc	core + jets + outer lobes, possibly misaligned	$< -0.6^{\dagger}$	few$\times 10\%^{\dagger}$	May be anti-correlated	Hydra A
Classical Double*	few$\times 10^2$–10^3 kpc	core + jets	$< -0.6^{\dagger}$	few$\times 10\%^{\dagger}$	May be anti-correlated	Cygnus A
Associated with extinct/dying radio galaxies:						
AGN Relic‡	few$\times 10$ kpc	filamentary + some diffuse emission; more extended at low frequency	$\lesssim -1.5$	$\lesssim 20\%$	May be anti-correlated	A133
Phoenix‡	10^2 kpc	filamentary + some diffuse emission; more extended at low frequency	$\lesssim -1.5$	10–30%	merger/ accretion shocks	A85
Not associated with radio galaxies:						
Radio Gischt‡	few$\times 10^2$–10^3 kpc	possible filaments, mostly diffuse; often two symmetric sources	$\lesssim -1.2$	10–30% lin.	Merger shocks	A3667
Mini-Halo	few$\times 10^2$ kpc	diffuse, centrally peaked	< -1.5	$\lesssim$ few%	Correlated	Perseus
Halo	$\gtrsim 10^3$ kpc	diffuse, centrally peaked, may be asymmetric, may have substructure	$\lesssim -1.1$	none	Correlated	1E0657-56

*Rare at low redshift.
†Frequency dependent.
*Variable across source.
‡Often called "radio relic" in the literature.

with inferred superluminal motion (for an early review, see Cohen & Unwin 1982). Circular polarization at the level of $\lesssim 1\%$ is observed in some sources (Homan 2000), while linear polarization at the level of a few percent is also detected in some sources (Enßlin 2003 and references therein). The spectrum of the black hole core is usually flat, while the jets have typical spectral indices of $\alpha \sim -0.5$, where $S_\nu \propto \nu^\alpha$. These sources are often observed in the cores of larger scale radio sources, e.g. M87 (Schmitt & Reid 1985).

Confined Cluster Core (CCC) Source: These small (~ 10 kpc) sources have been the subject of much study recently with the advent of X-ray observations with high angular resolution. The sort of "bubbles" discovered by *ROSAT* in the core of the Perseus cluster have now been seen with *Chandra* in many cooling flow clusters (Fabian et al. 2000; Blanton et al. 2001, and others). Unlike the more extended FR I radio galaxies, these sources often do not show two distinct radio lobes. While individual lobes may be visible, they are usually embedded in a halo of diffuse radio emission that extends in all azimuthal angles around the source center. When visible, the radio lobes are often quite distorted, as in the Centaurus cluster (Taylor, Fabian, & Allen 2002). These sources are typically found at the centers of cooling flow clusters, where the high density of the ICM confines the radio plasma, creating the amorphous morphology

of these sources. As the radio sources interact strongly with the ICM, they inflate large holes or "bubbles" in the hot gas. Bubbles from previous epochs of AGN outburst are occasionally seen at larger distances from the center of the cluster and are sometimes filled with older radio plasma, as is the case with at least one of the outer bubbles in the Perseus cluster (Fabian et al. 2000). It should be noted that these are not the only radio sources that inflate bubbles in the ICM.

These sources should not be confused with classical FR I radio galaxies which have much more distinct jets and radio lobes and are generally larger in physical extent. CCC sources may or may not have clearly distinguishable jets, even when more distinct lobes are visible. For example, the prototypical CCC source, 3C 84 at the center of the Perseus cluster, has visible jets (Liu & Zhang 2002), while another well studied source, A2052, does not (Blanton et al. 2001) They do, however, frequently have a bright, distinct core. As mentioned above, CCC sources are generally found in cooling flow clusters and not in less relaxed clusters where the ICM is less dense and may not be stable for long enough to enable X-ray bubbles to be inflated.

Radio Galaxy (FR I, WAT, and NAT): Unlike the previous class of sources, these classical radio galaxies have well defined jets with expanded envelopes, or lobes, at larger radii. Hydra A is a perfect example

of a classical FR I. The symmetric jets typically extend on the order of 10 kpc before the outer envelope forms. Outside this radius, the jets expand into radio lobes that are typically anti-correlated with the X-ray emission (McNamara et al. 2000). It is not clear at this time whether the separation of the outer envelope from the jets is caused by a drop in the density of the ICM or vice versa. The X-ray bubbles created by these sources are seen at a greater distance from the cluster center than are the bubbles created by confined cluster core sources.

At larger radii, some (and maybe all, if imaged with enough sensitivity) FR I sources show faint, extended emission beyond the brighter radio lobes. For example, deep radio observations of Hydra A have revealed much more extended radio emission beyond the well studied inner lobes (Lane et al. 2003; Taylor 2003). This emission is typically misaligned with the inner jets and lobes. An extreme example of this misalignment is seen in A2029, where the outer emission extends almost perpendicular to the inner lobes (Taylor, Barton, & Ge 1994). For this reason, this source may also be categorized as a wide angle tail (WAT) source. Unlike the inner radio lobes, these outer lobes are not necessarily anti-correlated with the X-ray emission. The bending of the lobes in WATs is believed to be caused by motion of the host galaxy relative to the ICM in which it is embedded. Some radio galaxies with particularly large velocities relative to their host clusters have their jets bent so much that they merge into a single extended tail behind the galaxy. These sources are known as narrow angle tails, or NATs.

Classical Double or FR II: The prototypical classical double radio galaxy is Cygnus A, appearing fairly linear and symmetric at low resolution, with bright hot spot regions near its termini. Unlike Cygnus A, most classical doubles are not found in rich clusters. These radio galaxies typically have weak jets, if any, and often only one is visible, perhaps because of relativistic beaming. They have sizes of order 100 kpc, higher luminosities than the other types of sources discussed here ($P_{1.4\,\mathrm{GHz}} > 10^{25}$ W Hz^{-1}; Ledlow & Owen 1996) and are associated with giant elliptical galaxies. Their bright bridges of emission, connecting the hot spot regions with the core, have progressively steeper radio spectra toward the core, commonly interpreted as being due to radiative aging of the relativistic electrons as these flow back from the shocks in the hot spots. The term FR II (Fanaroff and Riley type II, hot spots greater than one half distance to the terminus) is often used to denote these sources.

2.2. *Sources Associated With Extinct or Dying AGN*

AGN Relic: Of the several types of sources commonly referred to as "radio relics," sources associated with extinct or dying AGN are the only ones where the name is appropriate. We propose to reserve the term "relics" for these objects that are indeed relic radio galaxies where the AGN outburst that created the radio lobes has switched off, leaving the radio plasma to passively evolve. Because of the relatively short radiative lifetimes of the electrons in radio lobes, these sources are necessarily found near their source galaxies, in the central 10s of

kpc of the cluster. These sources are often quite filamentary when observed with sufficient angular resolution, as is the case with the relic in A133 (Slee et al. 2001). While the relic in A133 does not at first appear to be an obvious relic radio lobe, an analysis of the *Chandra* observation of the cluster showed this to be the most likely scenario (Fujita et al. 2002). A similar source has been found in MKW 3s, where a cold, bright finger of X-ray emission leads to a filamentary radio source (Slee et al. 1998; Mazzotta et al. 2002). Recent multi-wavelength observations by Young and collaborators have highlighted the radio bridge connecting the filamentary source back to an AGN at the center of the cluster (Young 2003).

As AGN relics age, their electrons will lose so much energy that their momentum spectra will eventually steepen to the point where they do not emit significant radiation at high frequencies and will appear simply as X-ray cavities with no observable radio emission. A theoretical discussion of these "radio ghosts" was outlined by Enßlin (1999). At later times, the emission may only be observable at frequencies below the limits of today's instruments. The planned low-frequency observatories LOFAR[1] and SKA[2] may be able to detect radio emission from these ghost cavities where current instruments fail.

Radio Phoenix: Previously known as radio relics, this class of object has one foot in each of two of our larger classes. With their origin as radio galaxies, these sources are clearly related to AGN, but they would not exist without being acted upon by the ICM. These sources begin their lives as true relics, but with a population of electrons that have aged so much as to be no longer emitting synchrotron radiation at currently observable radio frequencies (although LOFAR and/or the SKA may make such sources visible). When a merger shock or accretion shock from a cluster merger passes through such a faded relic, it will compress the fossil radio plasma. Because the density in the fossil plasma is expected to be much lower than that in the surrounding ICM, these shocks may become subsonic compression waves inside the plasma, as shown by Enßlin & Gopal-Krishna (2001) and Enßlin & Brüggen (2002). They also showed that these compression waves are capable of re-accelerating the electrons in the fossil plasma to energies at which they will once again be visible in the radio. The fossil plasma is thereby "reborn" from its own ashes to become a radio phoenix.

It is possible to use radio observations performed at at least three different frequencies to determine the original spectral index of a radio phoenix. In this technique, color-color data is fit with a theoretical model for the spectrum of an aged electron population. Given the current spectral shape, the original spectral slope is uniquely determined under the assumption of a relativistic electron population with a constant spectral shape over the entire source. For example, this has been done for the steep spectrum source associated with the southwest subcluster in A85. An original spectral index of -0.85 was

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[1] http://www.lofar.org
[2] http://www.skatelescope.org

found, confirming its likely origin as fossil radio plasma from an extinct AGN (Young 2003).

2.3. *Sources Associated With the ICM*

Radio Gischt: For many years, these sources have been identified as "radio relics." The name "radio flotsam" has also been proposed for these sources, but is not in wide use. We propose the name "radio gischt," German for the froth or spray on the tops of ocean waves. This name derives from the physical interpretation of these sources as synchrotron radiation from electrons directly accelerated from the thermal plasma in shocks. This name may seem somewhat similar to "radio flotsam," but it more explicitly references the connection between the radio sources and the pressure waves (merger/accretion shocks) responsible for them.

As we already mentioned, these sources are believed to be synchrotron emission from electrons directly accelerated from the thermal plasma in merger/accretion shocks. The radiative lifetime of $\gamma \sim 10^{4-5}$ electrons is only on the order of 10^8 years, comparable to the sound crossing time of these radio sources, so the radio emitting electrons should roughly trace out the shocks themselves. Because these sources tend to be found far from the centers of clusters where the X-ray surface brightness is very low, no shocks have yet been detected in X-rays at the positions of radio gischt. However, Markevitch & Vikhlinin (2001) found an enhancement of the relativistic electron population relative to the thermal population at the location of a merger shock near the center of A665. This provides the most concrete evidence thus far of in situ acceleration of electrons to relativistic energies.

Since these sources are directly associated with merger shocks, they should often come in pairs, at least in the intermediate stages of mergers between clusters with relatively equal masses. These should be located on opposite sides of the cluster along the axis of the merger, with the individual radio structures elongated perpendicular to this axis. Only a few symmetric gischt have been seen to date, in A3667 (Röttgering et al. 1997; Johnston-Hollitt et al. 2002), A3376 (Murphy 1999; Bagchi 2002), and A1240 (Kempner & Sarazin 2001), and the last of these has yet to be confirmed by deep pointed observations.

Their spectra are quite steep ($\alpha \sim -1.2$), and they are frequently found to be linearly polarized at the level of about 10%–30% (e.g. A2256, Clarke & Ensslin 2001). They are generally found on the peripheries of clusters. Projection effects should reduce this tendency somewhat, as may be the case in A2256. The absence of other centrally located gischt can be explained if the sources are highly planar and thus have surface brightnesses too low to be seen if they are observed face-on.

Mini-Halo: Unlike radio gischt and halos (see below), which appear to be tied to on-going merger events in clusters, mini-halos sources are typically found at the centers of so-called cooling flow clusters. They range in size from a few hundred kpc to half a Mpc. Mini-halos are low surface brightness, steep spectral index regions of diffuse emission which are found around powerful radio galaxies at the cores of some clusters (e.g. PKS 0745-191:

Baum & O'Dea 1991; Perseus: Burns et al. 1992; Virgo: Owen et al. 2000; A2626: Rizza et al. 2000). These sources are expected to have very short radiative lifetimes due to the high magnetic fields present in cooling-flow cores (Taylor et al. 2002) and thus the particles must be re-accelerated or injected *in situ*. Unlike radio gischt and halos, however, these sources probably do not draw their energy from major merger events as there is an anti-correlation between the presence of large mergers and that of cooling-flows.

Gitti, Brunetti, & Setti (2002) propose that the energy required for the particle acceleration comes from the cooling flow. They suggest a model where the electrons are continually undergoing re-acceleration due to the MHD turbulence associated with the cooling-flow region. This model produces Fermi-type acceleration which would result in a particle population that steepens away from the cluster center. This seems to be in general agreement with observations of the Perseus mini-halo which shows spectral index steepening away from the cluster core (Sijbring 1993) although some evidence suggests this steepening may be an observational artifact (Enßlin, Pfrommer, & Vogt 2003; Pfrommer & Vogt 2003; Pfrommer & Enßlin 2003). Gitti et al. (2002) suggest that the mini-halos are rare due to the need for a careful balance in the ICM: there must be sufficient turbulence to balance the radiative losses of the particles but not so much turbulence that it disrupts the cooling-flow.

A model for the formation of mini-halos, in which the relativistic electrons are accelerated by MHD turbulence in cooling flows, is presented by Gitti et al. (2003) in the proceedings of this conference.

Pfrommer & Enßlin (2003), on the other hand, propose a hadronic origin of these radio mini-halos: hadronic interactions of cosmic ray protons with ambient thermal protons produce synchrotron emitting relativistic electrons. Azimuthally averaged radio surface brightness profiles of the Perseus mini-halo matches the expected emission by this hadronic scenario well on all scales. Moreover, the small amount of required energy density in cosmic ray protons ($\sim$2% relative to the thermal energy density) supports this hypothesis not only because cosmological simulations carried out by Miniati et al. (2001) easily predict a population old cosmic ray protons at the clusters center of this order of magnitude.

Radio Halo: Like radio gischt, these sources are also believed to be the products of mergers between roughly equal mass clusters. Thus far, they have only been found in clusters currently undergoing or on the tail end of a merger. Their radio power appears to be strongly correlated with the X-ray luminosity of the host cluster (Liang et al. 2000; Feretti 2000), although the observational selection effects that may contribute to this relation have not yet been fully explored. Liang et al. (2000) also suggest a relation between radio power and X-ray temperature, although this relation has a much larger scatter and can be understood as simply a combination of the P_ν–L_X relation and the well known L_X–T_X relation.

The current leading hypothesis for the origin of the

relativistic electrons that create these sources is that they are re-accelerated, probably by turbulence, from a population of relatively low energy ($\gamma \sim 10^3$) electrons. This mildly relativistic pool may in turn have its origin in the merger shocks that cause radio gischt. As mentioned above, electrons with $\gamma \sim 10^{4-5}$ have very short lifetimes whereas $\gamma \sim 10^3$ electrons have lifetimes of order a few times 10^9 years, so any electrons accelerated in gischt would be capable of providing this suprathermal pool later in the merger while not actively emitting synchrotron radiation in the absence of a mechanism of re-acceleration. Fujita, Takizawa, & Sarazin (2003) demonstrated that turbulence may be capable of this re-acceleration in the case of roughly equal mergers between high mass systems. Turbulence has the attractive feature that it is directly connected to the local properties of the ICM and therefore should create radio emission that is correlated with local variations in the ICM. This connection has been demonstrated in a number of clusters, where strong correlations have been measured between the surface brightness distribution of radio halos and their host clusters' X-ray emission (Govoni et al. 2001a,b).

Another scenario, less favored at the moment but still plausible, is so-called secondary electron model proposed originally by Dennison (1980) and examined in more detail by Blasi & Colafrancesco (1999) and Dolag & Enßlin (2000). This model produces the radio-emitting electrons as a byproduct of hadronic interactions between cosmic ray protons (CRp's) and and the ambient thermal gas. Because they have lifetimes greater than a Hubble time, CRp's from a central AGN can diffuse throughout a cluster, producing the observed large scale emission. The steep falloff of the emission predicted by these models, however, does not match the observations of halos (Dolag & Enßlin 2000; Govoni et al. 2001a; Brunetti 2002) but may still fit those of mini-halos (see above and Enßlin et al. 2003; Pfrommer & Enßlin 2003).

Spectra of these sources are similar to those of gischt, though slightly flatter ($\alpha \sim -1.1$). Unlike gischt, however, radio halos are completely unpolarized.

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